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Management of Resistance in *Bemisia* in Arizona Cotton*

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Abstract: A whitefly (*Bemisia argentifolii*) resistance crisis climaxed in 1995 in Arizona cotton and prompted the development of an integrated resistance management strategy adapted from a program implemented in Israel in 1987. The strategy incorporated two new major elements: once-per-year use of the insect growth regulators (IGRs) pyriproxyfen and buprofezin, and measures to delay use of pyrethroids for as long into the growing season as possible. A three-stage chemical use recommendation was formulated comprising IGRs (Stage I), other non-pyrethroid insecticides (Stage II), and synergized pyrethroid insecticides (Stage III). Results from use of the strategy in the 1996 season were very promising. Insecticide use for control of whiteflies was reduced substantially. Statewide monitoring of whitefly susceptibility revealed significant reductions in resistance to synergized pyrethroids as well as increased susceptibility to amitraz. Susceptibility of Lygus bugs to key insecticides changed correspondingly with increases and decreases in whitefly resistance from 1994 through 1996.

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1 CHRONICLE OF A RESISTANCE CRISIS

Since the late 1980s, the silverleaf whitefly, *Bemisia argentifolii* Bellows and Perring has severely threatened production of cotton, melons, vegetables and ornamental crops in the southwestern deserts of the United States. While a broad range of integrated management tactics has been developed to suppress this pest, insecticides continue to play the prominent role in whitefly control programs of this region. As has been observed elsewhere in the world where this pest occurs, *Bemisia* in Arizona has rapidly developed resistance to essentially all groups of registered insecticides used against it.

Intensive reliance on a limited range of synergized pyrethroid insecticides resulted in a resistance crisis in Arizona cotton, first detected in 1994.[1] By the end of the 1995 season, pyrethroid insecticides synergized by organophosphates or carbamates failed to control whiteflies throughout much of Central Arizona cotton, as illustrated by data from the Maricopa Agricultural Center (Figs 1, 2). A classic resistance treadmill ensued, the end product of which was growers in the most seriously affected areas applying eight to 12 whitefly treatments, and cotton discounted by buyers due to honeydew contamination, in some cases despite insecticide expenditures of \$200–\$300 per acre.

In this paper the major elements of the program that was devised and implemented in 1996 to overcome

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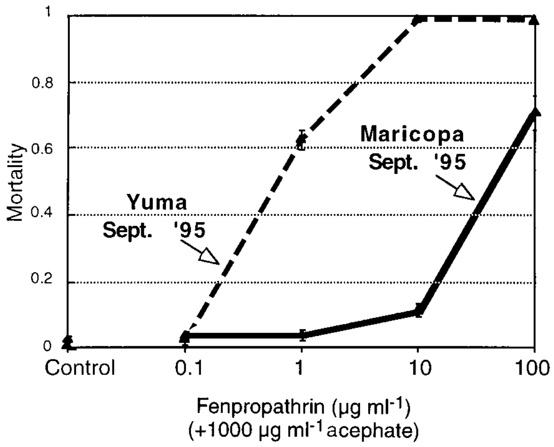

Fig. 1. Intensity of whitefly resistance to synergized pyrethroids as depicted by laboratory bioassays of susceptibility to mixtures of variable concentrations of fenpropathrin and a fixed concentration of acephate. Ref. 18.

whitefly resistance in Arizona are described and current results of this program summarized.

2 FORMULATING A SOLUTION

2.1 International collaboration

A speedy response to the Arizona whitefly crisis of 1995 was made possible by the cooperation of scientists from England (IACR-Rothamsted) and Israel (Gilat Regional Experiment Station and the Volcani Center, Bet Dagan). Rothamsted scientists shared their considerable experience with whitefly bioassay methods, isolation and description of whitefly resistances[2,3] and tactics for managing pesticide resistance.[4] Similarly pivotal to development of the new strategy in Arizona was Israeli experience with insect growth regulators. In the late 1980s, cotton growers in Israel faced serious whitefly resistance to pyrethroid insecticides. To overcome the problem, they formulated a successful resistance management program centered around the strategic use of insect growth regulators.[5] The benefits gained by Arizona cotton from this international collaboration illustrate clearly the value of global exchange of resistance information for the purpose of devising resistance management programs.

2.2 Southwest Whitefly Resistance Working Group

Resistance management requires cooperation and consensus-building of pest managers at a regional level. An essential step in Arizona's efforts to manage whitefly resistance has been the formation of the Southwest Whitefly Resistance Working Group. Since 1994, this group has met twice per year to reach consensus on recommendations for whitefly control in the Southwest deserts. Members of the group include university and government workers involved in cotton pest management in the Southwest and representatives from the regional and national cotton grower associations.

2.3 The Arizona Cotton Growers Association and Cotton Incorporated

Effective resistance management efforts require producer involvement and support. The Arizona Cotton Growers Association and Cotton Incorporated have served pivotal roles in this regard. They assisted with formulation of the 1996 strategy, with production of publications, and have supported educational programs in resistance management around the State. Both organizations have invested heavily in resistance

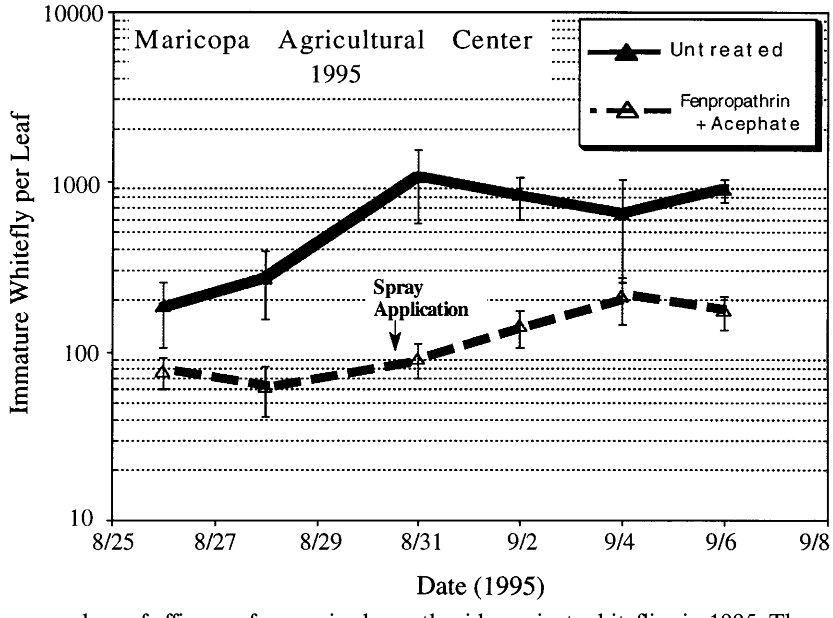

Fig. 2. Illustration of the severe loss of efficacy of synergized pyrethroids against whiteflies in 1995. The arrow indicates the date of a field treatment of fenpropathrin + acephate using conventional application rates and equipment. Ref. 18.

research. Doing so has required the foresight to fund studies before the point at which resistance reaches crisis proportions. Additionally, they have been leading participants in negotiations with chemical producers and the US Environmental Protection Agency (EPA) as they relate to Section 18 exemptions for new insecticides. Clearly, the resistance management program we describe herein would not have been developed as rapidly, nor delivered as effectively, without the assistance of these producer organizations.

2.4 Arizona's Extension Resistance Laboratory

The Extension Arthropod Resistance Management Laboratory (EARML) at the University of Arizona serves a practical function in maintaining applied programs to document and manage pest resistance in Arizona. This first-of-its-kind Extension facility in the USA was established in 1994 with funding from the USDA-Western Cotton Research Laboratory, the Arizona Cotton Growers Association, Cotton Incorporated, and the University of Arizona. EARML reflects Arizona's response to the 1985 recommendation of the US National Research Council[6] that: 'Resistance detection, monitoring and management organizations be formed at the local or regional level and assume responsibility for education, coordination, and implementation of activities to deal with resistance problems.'

EARML activities include routine monitoring of resistance in key pests throughout Arizona, research to isolate and characterize specific resistances, and evaluation of resistance management strategies. The laboratory strives to serve as a bridge to fundamental research groups by providing access to resistant pests and to a range of applied resistance management studies underway throughout the State. Strong emphasis is placed on educational programs that stress limiting and diversifying chemical use to avoid resistance.

3 MAJOR ELEMENTS OF THE ARIZONA STRATEGY

Objectives of the 1996 Whitefly Resistance Management Program for Arizona Cotton were to: (1) conserve natural enemies, (2) limit insecticide use and (3) diversify the selection of insecticides used against whiteflies. To achieve these goals, two new major elements were recommended for whitefly control in Arizona cotton: once-per-season use of each of two selective insect growth regulators, pyriproxyfen and buprofezin, and delayed use of pyrethroid insecticides for as long into the growing season as possible. These new measures were incorporated into a three-stage chemical use strategy (Fig. 3) and were coupled with renewed emphasis on whitefly monitoring, thresholds[7] and agronomic and cultural methods for managing whiteflies.[8] The three

Stage I: Insect Growth Regulators

Threshold: 0.5–1 large nymphs per leaf disk
and
3–5 adults per leaf

IGR	Use Restrictions
Buprofezin (Applaud 70WP)	Use only once per season. Apply no sooner than 21 days after Knack.
Pyriproxyfen (Knack 0.86EC)	Use only once per season. Apply no sooner than 14 days after Applaud.

Stage II: Non-Pyrethroids

Threshold: 5 adults per leaf

When populations average more than five adults per leaf, use Stage II materials at least once before using Stage III materials, in order to delay the use of pyrethroid insecticides.

Rotate among classes of insecticides and among different insecticides within classes.

Do not use mixtures of more than two compounds.

Avoid using any active ingredient more than twice per season.

Stage III: Pyrethroid Mixtures

Threshold: 5 adults per leaf

Delay pyrethroid use for as long as is practical in the growing season.

Use pyrethroid insecticides no more than twice per season.

Rotate the classes of insecticides mixed with pyrethroids .

Fig. 3. The three stages of chemical use incorporated into the 1996 Whitefly Resistance Management Program for Arizona Cotton. Ref. 9.

stages of whitefly chemical use, Stage I, insect growth regulators, Stage II, non-pyrethroids and Stage III, pyrethroids, together with their respective sampling procedures and treatment thresholds, were described in an extension publication[9] that included a laminated pocket guide[10] detailing the efficacy of the various options for Stage II and Stage III insecticides.

With agreement reached in November 1995, on the specifics of the strategy and cooperation promised by the producers of the two IGRs (AgrEvo USA Company and Valent USA Corporation), the Arizona Cotton Growers Association set out to obtain approval from the EPA for the highly unusual request of emergency (Section 18) exemptions for the two insect growth regulators. The rationale supporting the dual exemptions was based on resistance management objectives. The application restricted use of both IGRs to once per year.

Time was very limited; there was less than six months remaining before the onset of another season of combating whitefly build-up in cotton. The University of Arizona's Cotton IPM Team Leader, Dr Peter Ellsworth, took the lead in compiling materials and drafting documents for the Section 18 request. In May 1996

both exemptions were granted, clearing the way for implementation of the resistance management strategy. In addition to limiting use of pyriproxyfen and buprofezin to once-per-season, the provisions of the Section 18 exemption required that all applicators obtain a certification that they had been properly trained in the use of these novel materials. This involved attending one of the IGR educational programs sponsored statewide by the Arizona Cotton Growers Association, AgrEvo, Valent and the University of Arizona Cooperative Extension. Additionally, the EPA mandated monitoring of grower compliance with the provisions of the Section 18 exemption. This has been done jointly by the Arizona Department of Agriculture and the Arizona Cotton Growers Association.

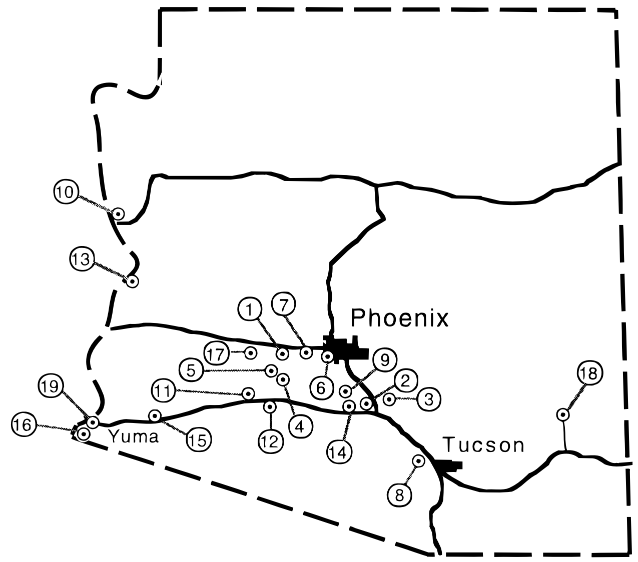

Fig. 4. Arizona locations from which whiteflies were collected and tested for susceptibility to key insecticides in 1996.

4 EVALUATING THE STRATEGY

Success of the Arizona whitefly resistance management strategy is evaluated firstly on the basis of short-term benefit to cotton growers, i.e. the degree to which in 1996 it overcame the resistance-related whitefly-control problems that plagued Arizona growers in 1995. Second, success will be judged on the degree to which the program has prolonged the useful lives of the insecticides used in Arizona cotton. Obviously, at this stage, we can speak confidently only about the former criterion. The longer-term question will be evaluated over the course of the coming years through documentation of whitefly control in cotton fields and through statewide monitoring of levels of whitefly resistance. The following is a summary of findings to date.

4.1 Monitoring of whitefly resistance to insecticides

Whitefly resistance levels were monitored in 1996 in populations collected at 19 locations throughout the major cotton production areas of Arizona (Fig. 4). Adult whiteflies were vacuum-collected directly from cotton foliage into plastic vials using a Makita® cordless vacuum (4071D). Samples were transported in ice chests directly to EARML where they were released into cages containing cotton plants, *Gossypium hirsutum* L (DPL-50). Adult whitefly were maintained in these cages until they were used for bioassays (less than seven days). Susceptibility of each population was estimated to the following insecticide treatments: (1) profenofos + chlorpyrifos (1 + 1); (2) profenofos + oxamyl (1 + 1); (3) endosulfan; (4) a fixed concentration of acephate (1 mg ml^{-1}) combined with varying concentrations of fenpropathrin; (5) amitraz; and (6) amitraz + endosulfan (1 + 1).

A derivative of the Rothamsted leaf disc bioassay method[11] was used. Leaf discs, (2·5 cm diam.) were taken from 18- to 26-day-old cotton plants (DPL-50) and dipped for 10 s in formulated insecticide diluted with distilled water. After drying, the discs were placed individually on a base of agar (13 g litre^{-1}) within 20-ml glass scintillation vials. Within 2 h of dipping, 20–30 adult whiteflies were aspirated into each vial, vials were capped with dialysis tubing, inverted and held in an incubator at 27($\pm$1)°C for 48 h, after which they were scored using a binocular dissecting microscope. Vials were tapped on the counter 10 times; whiteflies not exhibiting repetitive movement of more than one appendage were scored as dead.

At least five different concentrations and six bioassay replications per concentration were evaluated for each insecticide/population combination tested. Statistical significance of locational effects (population sampled), concentration effects, and interactions for each insecticide was evaluated initially using ANOVA.[12] The dependent variable was percentage mortality from each replicate of each concentration evaluated, transformed using arcsin $\sqrt{x}$. Susceptibility data from many of the insecticides/populations evaluated departed significantly from normality and/or variances were unequal between treatments. In such cases median tests (PROC NPAR1WAY)[12] were used to compare whitefly mortality across all locations between 1995 and 1996 for specific insecticide/concentration combinations.

4.1.1 *Synergized pyrethroids*

Overall, whiteflies from throughout Arizona were substantially more susceptible to the synergized pyrethroid mixture of fenpropathrin + acephate after deployment of the resistance management strategy in 1996 than in 1995 (Tables 1, 2). Severe resistance to the synergized pyrethroids in 1995 was correlated with $<30\%$ mortal-

TABLE 1
Mortality of Arizona Silverleaf Whitefly Populations Collected in 1996 and Tested in Leaf-Disc Bioassays with Fenpropathrin plus acephate.[15]

		Whitefly mortality (%) (±SD)				
		Fenpropathrin conc. (μg ml^{-1})[a]				
No.[b]	*Location*	*0*	*0·1*	*1*	*10*	*100*
1	Buckeye	0 (±0)	4·7 (±5·5)	15 (±12)	45 (±20)	98 (±3·6)
2	Casa Grande	3·0 (±4·0)	4·5 (±7·4)	37 (±11)	62 (±13)	92 (±6·5)
3	Coolidge	3·7 (±3·9)	10 (±8·1)	26 (±8·9)	59 (±14)	96 (±9·3)
4	Gila River Basin #1	2·6 (±2·9)	8·7 (±7·7)	33 (±14)	59 (±14)	94 (±4·5)
5	Gila River Basin #2	1·6 (±2·7)	3·3 (±3·7)	8·2 (±7·1)	27 (±14)	86 (±17)
6	Laveen	3·0 (±3·6)	3·1 (±3·7)	19 (±13)	53 (±17)	99 (±1·6)
7	Litchfield Park	14 (±9·5)	14 (±8·6)	23 (±12)	52 (±7·1)	94 (±9·0)
8	Marana	0 (±0)	7·2 (±3·8)	75 (±9·7)	96 (±1·8)	100 (±0)
9	Maricopa Ag. Ctr.	2·0 (±2·2)	16 (±12)	40 (±13)	75 (±11)	96 (±2·9)
10	Mohave Valley	3·0 (±3·6)	10 (±8·7)	55 (±19)	92 (±3·2)	100 (±0)
11	Painted Rock	0·76 (±1·9)	2·7 (±4·6)	5·5 (±3·3)	46 (±7·9)	71 (±11)
12	Paloma	0·69 (±1·7)	1·3 (±2·1)	25 (±10)	48 (±5·4)	100 (±0)
13	Parker	17 (±10)	15 (±8·3)	48 (±22)	94 (±6·8)	100 (±0)
14	Peters Corner	1·4 (±2·2)	3·0 (±3·6)	31 (±6·0)	59 (±15)	95 (±6·5)
15	Roll	2·0 (±3·4)	8·3 (±9·4)	57 (±9·9)	83 (±10)	97 (±3·7)
16	Somerton	3·6 (±1·8)	2·5 (±2·7)	63 (±16)	96 (±3·4)	100 (±0)
17	South Harquahala Valley	0·72 (±1·8)	6·6 (±5·6)	41 (±11)	81 (±11)	100 (±0)
18	Thatcher	4·8 (±3·8)	6·5 (±8·4)	85 (±9·6)	98 (±2·5)	100 (±0)
19	Yuma Valley Ag. Ctr.	1·5 (±2·4)	6·9 (±9·8)	68 (±17)	94 (±4·6)	92 (±7·6)
1996	*Summary*	*Statistics*				
	N	19	19	19	19	19
	Mean	3·5	7·2	40	70	95
	Median	2·0	6·6	37	62	97
	Minimum value	0	1·3	5·5	27	71
	S.D.	4·6	4·5	22	21	6·8

[a] In all cases with acephate at 1 mg ml^{-1}.
[b] Site numbers as shown in Fig. 4.

ity (Fig. 1) in bioassays of whitefly treated with fenpropathrin + acephate (10 + 1000 μg ml^{-1}).[13] Such intensely resistant populations were detected at only one of 19 locations in 1996 (Table 1), whereas they were found at four of 13 sites in 1995 (Table 2).

Median tests comparing mortality in bioassays of fenpropathrin + acephate in 1995 versus 1996 showed significant differences for the 100 μg ml^{-1} concentration ($P < 0{\cdot}0001$), confirming the overall increased susceptibility of Arizona whitefly populations in 1996. Sizeable reductions in resistance to fenpropathrin + acephate were also apparent from inspection of the results of bioassays of 10 μg ml^{-1} treatments for specific locations in 1995 versus 1996 (Tables 1, 2), but were not statistically significant at $a = 0{\cdot}05$. This lack of statistical significance resulted primarily from samples collected at two locations (Buckeye and Casa Grande) at which resistance to fenpropathrin + acephate increased substantially from 1995 to 1996 (Tables 1, 2). These two Central Arizona locations are in the vicinity of serious pyrethroid resistance problems but, as shown in Table 2, resistance levels at these locations were low in 1995. We conclude that producers at these two locations did not heed the recommendations of the resistance management strategy in 1996, because they had not experienced serious pyrethroid resistance in 1995. In contrast, at all of the locations from which we documented moderate-to-high whitefly resistance to pyrethroids in 1995, (≥50% survivorship of bioassays of fenpropathrin (10 μg ml^{-1}) + acephate treatments; Table 2), resistance levels declined in 1996. The *t*-interval ($a = 0{\cdot}05$) estimate of the magnitude of the increase in mortality from 1995 to 1996 in bioassays of 10 μg ml^{-1} was 4·4–49% for these locations (Tables 1, 2). Despite this striking reduction in whitefly resistance, significant regional differences in whitefly susceptibility to synergized pyrethroids continued to be found in 1996 (Table 1, Fig. 4).

Changes in resistance to pyrethroids were documented intensively in 1995 and 1996 at the Maricopa Agricultural Center (MAC), Maricopa, Arizona. Resistance to fenpropathrin + acephate was shown to be

TABLE 2
Mortality of Arizona Silverleaf Whitefly Populations Collected in 1995 and Tested in Leaf-Disc Bioassays with Fenpropathrin plus acephate.[13]

		Whitefly mortality (%) (±SD)				
		Fenpropathrin conc. (μg ml⁻¹)[a]				
No.[b]	*Location*	*0*	*0·1*	*1*	*10*	*100*
1	Buckeye	5·0 (±3·0)	4·4 (±5·9)	53 (±14)	89 (±8·8)	99 (±1·8)
2	Casa Grande	5·2 (±4·5)	6·9 (±3·0)	27 (±19)	89 (±11)	94 (±3·4)
4	Gila River Basin #1	21 (±15)	16 (±13)	27 (±12)	36 (±17)	99 (±2·1)
5	Gila River Basin #2	8·9 (±3·9)	7·0 (±3·6)	10 (±7·1)	19 (±7·5)	92 (±6·4)
6	Laveen	1·9 (±2·1)	1·3 (±2·0)	15 (±11)	54 (±13)	91 (±8·2)
7	Litchfield Park	1·9 (±2·2)	2·1 (±3·7)	12 (±6·3)	33 (±6·9)	96 (±2·1)
8	Marana	3·6 (±4·5)	6·6 (±3·7)	41 (±23)	97 (±2·5)	98 (±2·3)
9	Maricopa Ag. Ctr.	1·3 (±2·0)	3·0 (±2·3)	3·7 (±3·4)	19 (±10)	81 (±12)
11	Painted Rock	0·69 (±1·7)	1·8 (±3·0)	2·7 (±2·1)	7·8 (±5·5)	72 (±11·3)
12	Paloma	0 (±0)	2·8 (±3·4)	2·9 (±5·1)	8·7 (±4·9)	66 (±15)
13	Parker	32 (±24)	9·7 (±8·4)	85 (±7·0)	100 (±0)	100 (±0)
18	Thatcher	2·7 (±3·4)	1·9 (±2·1)	33 (±17)	97 (±2·1)	100 (±0)
19	Yuma Valley Ag. Ctr.	15 (±6·4)	17 (±17)	90 (±6·6)	100 (±0)	100 (±0)
1995	*Summary*	*Statistics*				
	N	13	13	13	13	13
	Mean	7·6	6·2	31	57	91
	Median	3·6	4·4	27	54	96
	Minimum value	0	1·3	2·7	7·8	66
	S.D.	9·5	5·2	29	38	11

[a] In all cases with acephate at 1 mg ml⁻¹.
[b] Site numbers as shown in Fig. 4.

unstable at this location, declining sharply from the end of the 1995 season to the beginning of the 1996 season (Fig. 5A). However, susceptibility was not regained fully to levels that existed early in 1995.

Optimism regarding the future of pyrethroids for whitefly control in Arizona cotton should be tempered by our findings from field trials that single treatments of fenpropathrin + acephate caused large increases in pyrethroid resistance (Fig. 5B). This confirmed our conclusion from 1995 that areas with histories of pyrethroid resistance were unlikely to obtain satisfactory results from more than two applications of synergized pyrethroids per season. This finding can now be extended to essentially all the pyrethroids used in Arizona for whitefly control. In extensive selection experiments conducted in cages at EARML,[14] resistance to fenpropathrin + acephate was shown to confer cross-resistance to all of the pyrethroids evaluated. The Arizona strategy recommended holding these synergized pyrethroids in reserve, to be used as a last resort, should they be needed late in the season when the crop is at greatest risk of being contaminated by honeydew.

With implementation of the new strategy in 1996, many Arizona growers were able to maintain control of whiteflies by using only Stage I and Stage II insecticides; that is, they did not find it necessary to use pyrethroids. Monitoring of resistance to synergized pyrethroids demonstrated that applications of the IGRs, pyriproxyfen and buprofezin, and the non-pyrethroid insecticide treatments, endosulfan + amitraz and profenofos + oxamyl, did not result in significant reductions in susceptibility to fenpropathrin + acephate (Fig. 5a). This is further evidence that the 1996 whitefly resistance management program yielded immediate benefits in terms of reduced selection for resistance to the synergized pyrethroids.

4.1.2 *Non-pyrethroid insecticides*

EARML has monitored whitefly susceptibility to pyrethroid and non-pyrethroid insecticides throughout the cotton growing regions of Arizona since 1994.[1,13,15] This has revealed that the 1996 Arizona whitefly resistance management strategy not only combated resistance to synthetic pyrethroids, but was also correlated with reduced resistance to at least one non-pyrethroid insecticide. Median tests comparing whitefly susceptibility to amitraz revealed statistically significant ($P < 0{\cdot}01$) increases in mortality from 1995 to 1996 of bioassay concentrations of 10, 100 and 1000 μg ml⁻¹ amitraz.[15] While not statistically significant, numeri-

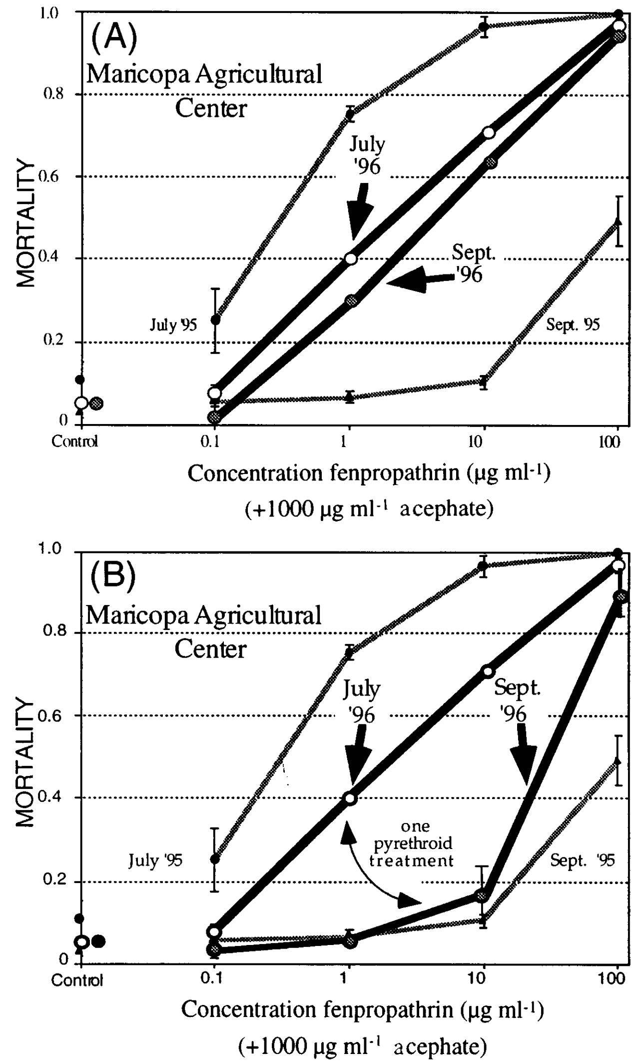

Fig. 5. Changes in whitefly susceptibility during 1995 and from September 1995 to July 1996 (prior to application of insecticides in 1996) as depicted by mean mortality (I = SD) in bioassays with fenpropathrin + acephate of whiteflies collected from the Maricopa Agricultural Center. Also shown is whitefly susceptibility at the end of the 1996 season: (A) in plots treated with only Stage I chemicals (pyriproxyfen and buprofezin) and Stage II chemicals (amitraz + endosulfan and profenofos + oxamyl) in 1996; (B) in plots treated with one application of a mixture of fenpropathrin + acephate in 1996. Ref. 15.

cally greater mean and median estimates of whitefly susceptibility to endosulfan were also documented.[15]

4.2 Control observed

Implementation of the 1996 strategy has been associated with immediate benefits of reduced insecticide use in Arizona cotton. Both grower experience[16] and large-scale demonstration trials[17] indicated excellent whitefly control at locations employing the strategy. In areas such as Gila Bend, where we documented the highest levels of pyrethroid resistance in 1995,[13,18] many of

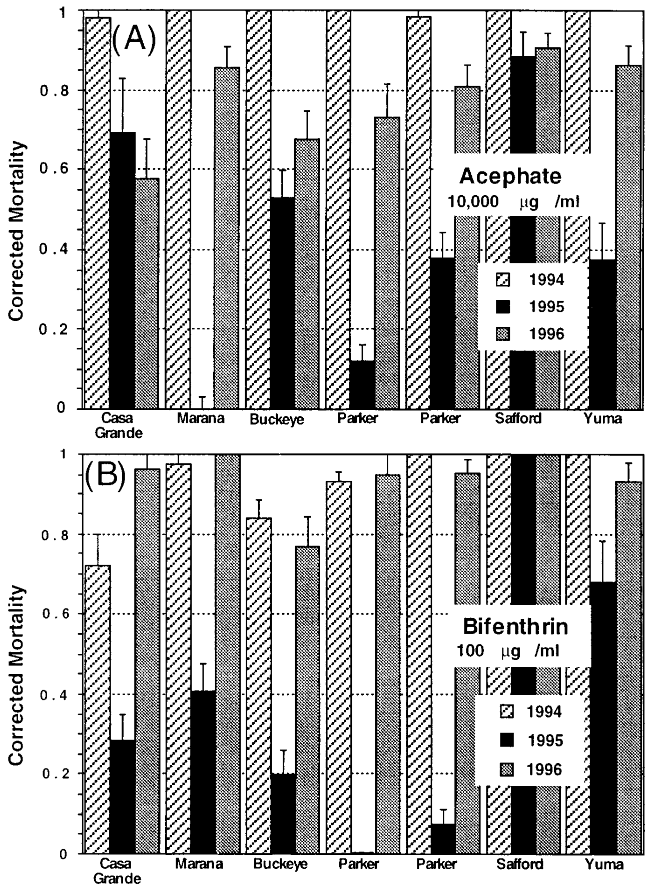

Fig. 6. Reductions in Arizona lygus bug susceptibility to insecticides coinciding with the whitefly resistance crisis that occurred in 1995. Shown is mortality (I = SEM) observed from 1994 through 1996 in vial bioassays with: (A) acephate (10 mg ml^{-1}) and (B) bifenthrin (100 μg ml^{-1}). Ref. 23.

those fields that received eight to 12 whitefly treatments in 1995 required only one to four insecticide applications in 1996.[16,19] On a state-wide basis, seasonal whitefly treatments per cotton field were estimated to have been reduced from 6·6 in 1995 to 1·9 in 1996 (P. C. Ellsworth, pers. comm.). If these reductions of overall selection pressure can be maintained state-wide, we will have made major advances toward sustaining the efficacy of cotton insecticides.

4.3 Collateral susceptibility changes of lygus bugs

Lygus bugs (principally *Lygus hesperus* Knight) are a key pest of Arizona cotton, causing economic losses through feeding on young floral buds, flowers and young bolls. Since 1994 we have been estimating susceptibility of lygus populations throughout Arizona to the pyrethroid, bifenthrin, and the organophosphate, acephate. Contrasts of lygus and whitefly susceptibility data provided evidence of collateral resistance build-up and decline on a state-wide basis. We reported substantially reduced susceptibility of lygus bugs in 1995, relative to 1994.[20] This reduction coincided with elevated use of

synergized pyrethroids during the 1995 whitefly resistance crisis. Implementation of the 1996 whitefly resistance management program was correlated with significantly increased lygus bug susceptibility at most locations monitored throughout Arizona (Fig. 6). These data affirm the validity of the resistance treadmill concept. Grower responses to whitefly resistance problems appeared to have made it more difficult to control lygus bugs, thereby necessitating further insecticide use and exacerbating further the economic losses associated with the resistance episode.

5 SUSTAINING AND IMPROVING THE STRATEGY

The whitefly resistance crisis in Arizona cotton was met by introduction of effective, selective insect growth regulators. These materials show clear signs of having re-established a degree of biological harmony in this system.[21] Yet, there are indications that pyriproxyfen and buprofezin are of relatively high resistance risk.[3,22] To sustain the successful whitefly control program, it is essential that the Arizona cotton industry continue to limit IGR use and maintain reliance on the non-chemical whitefly control measures detailed in the Arizona strategy.[7,9] State-wide monitoring of whitefly resistance will provide a way of tracking the future success of these efforts and will allow the strategy to be modified promptly should resistance to the IGRs emerge.

6 CONCLUSIONS

The program described has advanced resistance management in Arizona cotton from general concepts to specific actions that have demonstrated value for producers. Major strengths of the program are that: (1) it was derived through consensus-building by a working group composed of growers, representatives from grower organizations, chemical producers and researchers; (2) it is supported by diverse research efforts that foster reducing the overall use of insecticides in cotton; (3) it is coupled with long-term, state-wide detection of resistance and field evaluation of specific resistance management strategies; (4) it has a strong educational component that delivers the message of resistance management to every cotton-producing county *via* a diverse array of educational media and (5) it incorporates regulatory action that fosters compliance with critical aspects of the strategy *via* label restrictions. The program yielded immediate benefits in 1996 in terms of reduction in resistance and reduced numbers of whitefly treatments in Arizona cotton.

We are working with the Arizona Cotton Growers Association to foster a fundamental change in the manner in which insecticides are used in Arizona. Each year pesticides represent one of the cotton growers' largest variable production costs. Arizona growers know that they cannot maintain profitable cotton production in the face of the high costs associated with resistance crises such as beset them in 1995. Harmonizing chemical control to avert such problems will require limiting and diversifying insecticide use. Regulatory restrictions limiting IGR use to once-per-season and delaying or eliminating pyrethroid use constitute essential steps in that direction. Equally important to management of resistance is avoiding over-reliance on any given insecticide cross-resistance group. Doing so requires having a sufficient number of effective insecticides to allow diversification of the pesticide use regime. The willingness of the Environmental Protection Agency to grant dual Section 18 exemptions for pyriproxyfen and buprofezin reflected an important recognition of this fact.

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REFERENCES

1. Dennehy, T. J., Simmons, A. & Russell, J. S., Building a whitefly resistance management program for Arizona cotton. *University of Arizona Cooperative Extension Cotton Report*, 1995.
2. Byrne, F. J., Cahill, M., Denholm, I. & Devonshire, A. L., A biochemical and toxicological study of the role of insensitive acetylcholinesterase in organophosphorus resistant *Bemisia tabaci* (Homoptera: Aleyrodidae) from Israel. *Bull. Entomol. Res.*, **84** (1994) 179–84.

3. Cahill, M., Jarvis, W., Gorman, K. & Denholm, I., Resolution of baseline responses and documentation of resistance to buprofezin in *Bemisia tabaci* (Homoptera: Aleyrodidae). *Bull. Entomol. Res.*, **86** (1996) 117–22.
4. Denholm, I. & Rowland, M. W., Tactics for managing pesticide resistance in arthropods. *Annu. Rev. Entomol.*, **37** (1992) 91–112.
5. Horowitz, A. R., Control strategy for the sweetpotato whitefly, *Bemisia tabaci*, late in the cotton-growing season. *Phytoparasitica*, **21** (1993) 281–91.
6. Anon. *Pesticide Resistance: Strategies and Tactics for Management*. National Research Council, National Academy Press, Washington, DC 1986, 471 pp.
7. Ellsworth, P. C., Dennehy, T. J. & Nichols, R. L., Whitefly management in Arizona cotton 1996. *University of Arizona IPM, Series* No. 3, 1996.
8. Byrne, D. N. & Bellows, T. S., Whitefly biology. *Annu. Rev. Entomol.*, **36** (1991) 431–57.
9. Dennehy, T. J., Ellsworth, P. C. & Nichols, R. L., The 1996 whitefly resistance management program for Arizona cotton. *University of Arizona IPM Series* No. 8, 1996, 16 pp.
10. Ellsworth, P. C. & Watson, T. F., *Whitefly in Arizona: pocket guide '96*. University of Arizona Cooperative Extension (laminated card), 1996.
11. Rowland, M., Pye, B., Stribley, M., Hackett, B., Denholm, I. & Sawicki, R. M., Laboratory apparatus and techniques for the rearing and insecticidal treatment of whitefly, *Bemisia tabaci*, under simulated field conditions. *Bull. Entomol. Res.*, **80** (1990) 209–16.
12. SAS/STAT® *User's Guide*, Version 6, 4th edn. SAS Institute Inc., Cary, NC, 1989, 846 pp.
13. Dennehy, T. J., Williams, III, L., Russell, J. S., Li, X. & Wigert, M., Monitoring and management of whitefly resistance to insecticides in Arizona. *Proc. Beltwide Cotton Conf.*, 1996, pp. 743–8.
14. Sivasupramaniam, S., Dennehy, T. J. & Williams, III, L., Management of pyrethroid-resistant whiteflies in Arizona cotton: selection, cross-resistance and dynamics. *Proc. Beltwide Cotton Conf.*, 1997.
15. Dennehy, T. J., Williams, III, L., Li, X., Wigert, M. & Birdwell, E., Status of whitefly resistance to insecticides in Arizona Cotton. *University of Arizona Cooperative Extension Cotton Report*., 1997.
16. Jech, L. E. & Husman, S. H., Gila Basin voluntary pest management project, 1995 and 1996. In *Cotton: A College of Agriculture Report. Series P-108*. University of Arizona Cooperative Extension, 1997, pp. 225–31.
17. Ellsworth, P. C., Diehl, J., Kirk, I. W. & Henneberry, T. J., *Bemisia* growth regulators: large-scale evaluation. *Proc. Beltwide Cotton Conf.*, 1997.
18. Simmons, A. L. & Dennehy, T. J., Contrasts of three insecticide resistance monitoring methods for whitefly. *Proc. Beltwide Cotton Conf.*, 1996, pp. 748–52.
19. Simmons, A. L., Williams, III, L. & Dennehy, T. J., Investigations of two insect growth regulators against Arizona whitefly populations. *Proc. Beltwide Cotton Conf.*, 1997,.
20. Dennehy, T. J. & Russell, J. S., Susceptibility of lygus bug populations in Arizona to acephate (Orthene®) and bifenthrin (Capture®) with related contrasts of other insecticides. *Proc. Beltwide Cotton Conf.*, 1996, pp. 771–7.
21. Naranjo, S. E. & Hagler, J. R., *Bemisia* growth regulators: conservation of natural enemies. *Proc. Beltwide Cotton Conf.*, 1997.
22. Horowitz, A. R., Forer, G. & Ishaaya, I., Managing resistance in *Bemisia tabaci* in Israel with emphasis on cotton. *Pestic. Sci.*, **42** (1994) 113–22.
23. Russell, J. E., Dennehy, T. J., Antilla, L., Whitlow, M., Webb, R. & Pacheco, J., Lygus bugs in Arizona regain susceptibility to key insecticides. *Proc. Beltwide Cotton Conf.*, 1997.